

PEBB PowerModule™ Program

by
Perry Schugart

PEBB PowerModules

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Power Electronic Systems

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Contractor Name American Superconductor
Contractor Address Two Technology Drive
Westborough, MA 01581

Expiration Date March 4, 2007

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Superconductor
Contractor Address Two Technology Drive

Westborough, MA 0158

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Agenda

Power Electronic Systems

- **Low Voltage PEBB Overview**
- **PM1000 PowerModule™ Test Results**
- **PM1000 Human-Machine-Interface**
- **Medium Voltage PEBB Overview**
- **PowerModule Flexibility**

PEBB LV Project

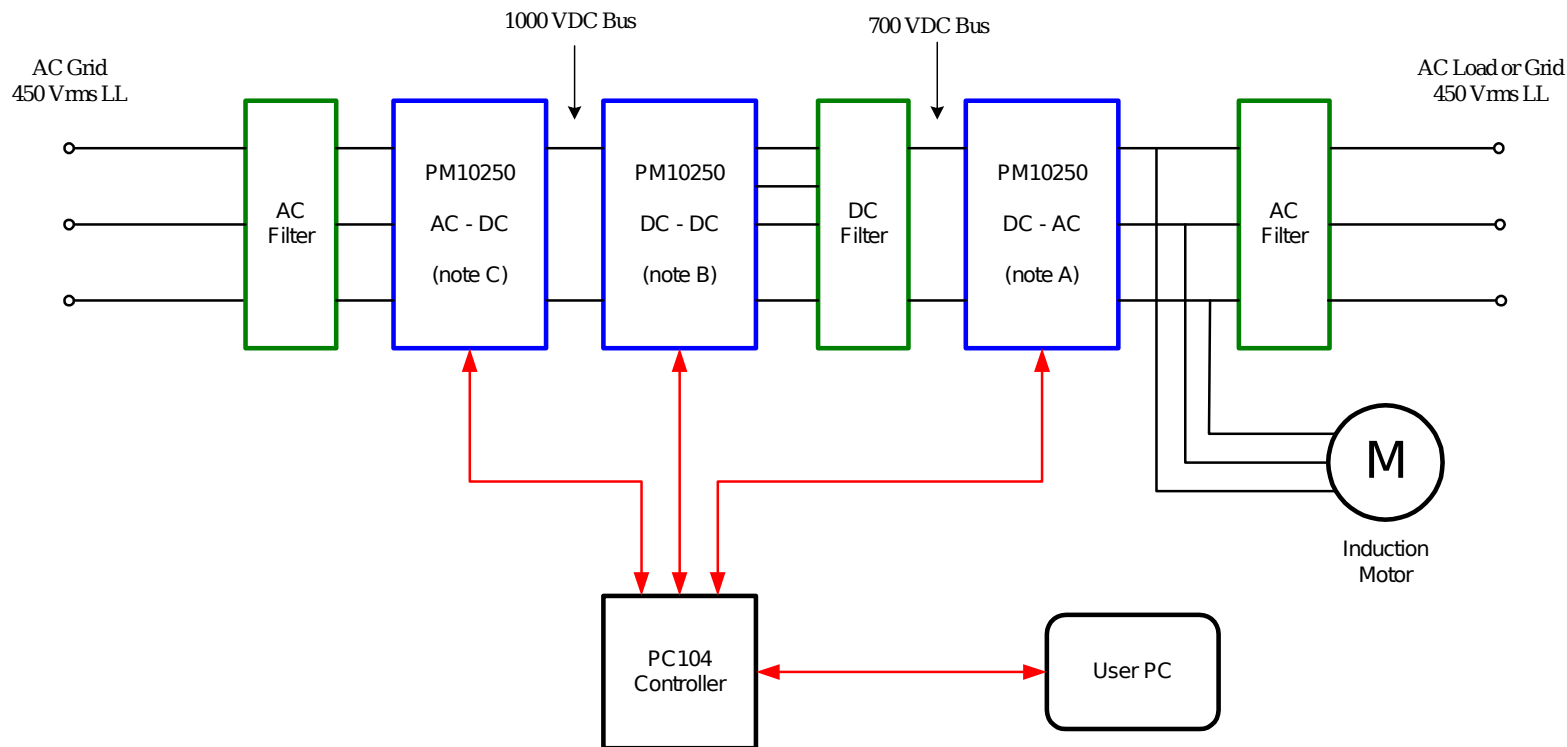
Power Electronic Systems

Mission

- **To develop a low voltage power conversion system using a power electronics building block format to meet the PEBB requirements. The system will be based on the PM1000 architecture.**
- **The system includes:**
 - **3 phase AC-DC Converter ($450V_{AC}$ - $1,000V_{DC}$)**
 - **3 pole DC-DC Buck Converter ($1,000V_{DC}$ - $700V_{DC}$)**
 - **3 phase DC-AC Converter ($700V_{DC}$ - $450V_{AC}$)**
 - **PC104 based System Controller**

PEBB LV System

Power Electronic Systems



Note C

- 1) Based upon PM1000 (6 poles) with 1100 VDC bus
- 2) Uses 1700V IGBT in new package
- 3) Active rectifier operation

Note B

- 1) Based upon PM1000 (3 poles) with 1100 VDC bus
- 2) Uses 1700V IGBT in new package
- 3) Bidirectional DC to DC operation
- 4) 3 pole interleaved PWM design

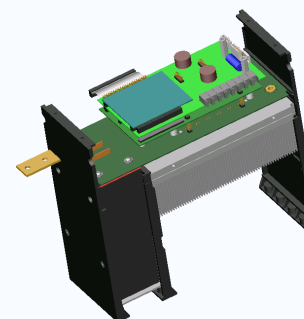
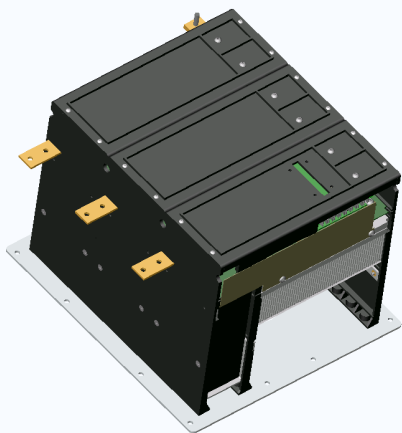
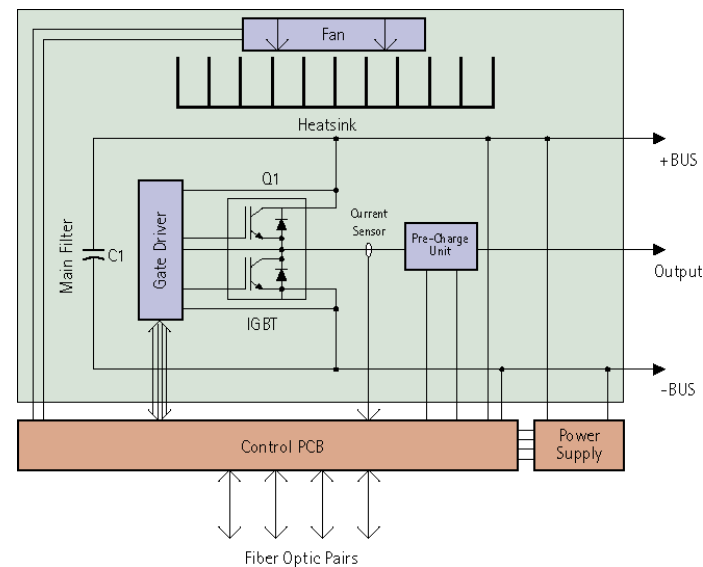
Note A

- 1) Based upon PM1000 (6 poles) with new IGBT package design
- 2) Uses 1200V IGBT w/ SiC Diode
- 3) 3 wire UPS and motor drive operation

Integrated Modularity - the PM1000

Power Electronic Systems

- High Power Densities
- Minimal Interconnects
- Self Contained
- Fully Programmable
- Fiber Optic Communications
- Isolated Cooling Path
- Direct Waveform Control



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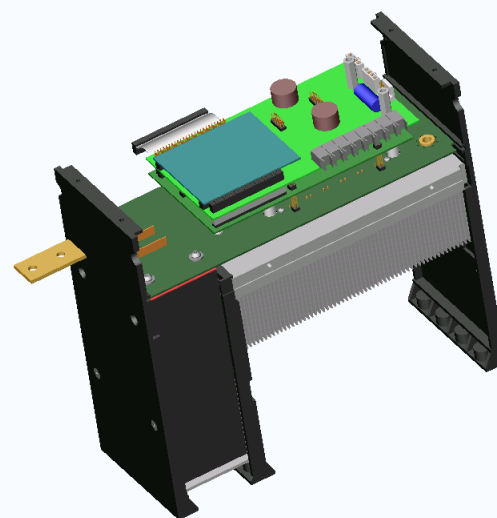
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Power Circuit

Power Electronic Systems

- Pole based design
- PCB based power circuit
- Soldered IGBT - Econopack
- Non-Electrolytic Bus Capacitor
- Integrated current sensing
- Gate drivers
- Auxiliary power supply
- Integrated cooling
- Operates without a ground reference



Control and Protection

Power Electronic Systems

■ Control Features

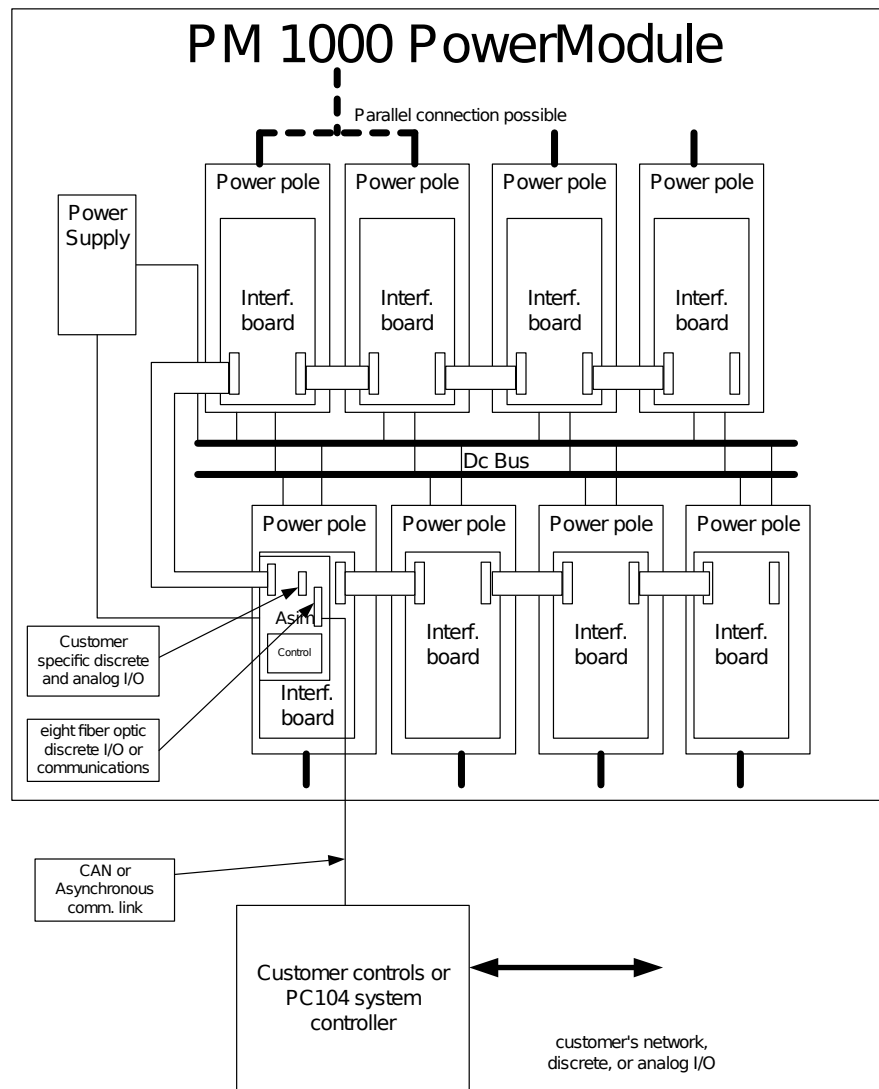
- Dual DSP (80 MHz) with integrated PWM control
- 8 pole control
- 8 kHz PWM (Standard)
- CPLD for hardware protection and signal routing
- Algorithms for multiple operating modes
- Analog and digital I/O

■ Hardware Protection

- Over current
- Over temperature
- IGBT De-saturation
- Bus over voltage
- Power supply monitors
- Fan monitor
- Precharge monitor

PCB Based PowerModule

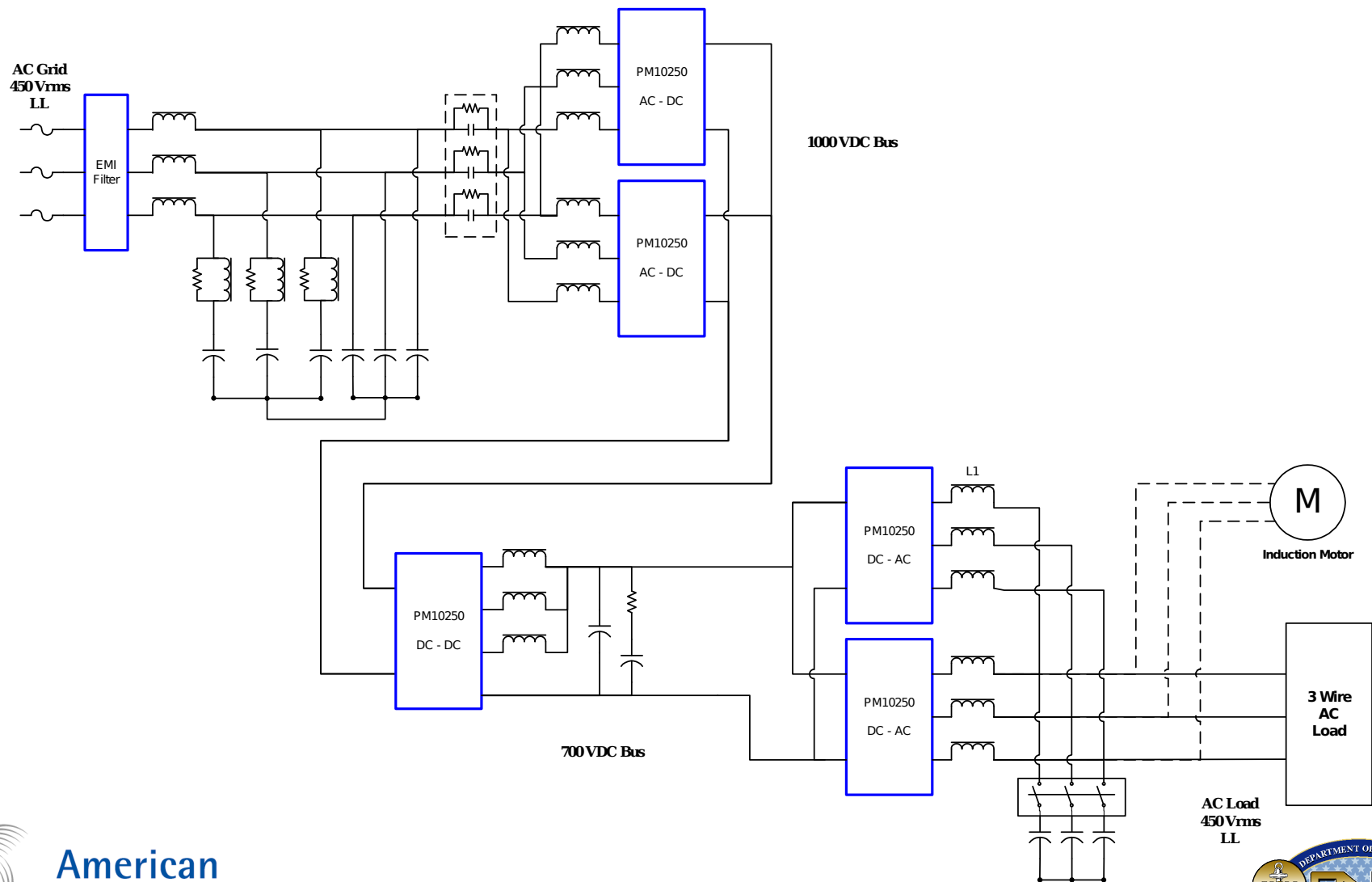
Power Electronic Systems



Limited Rights

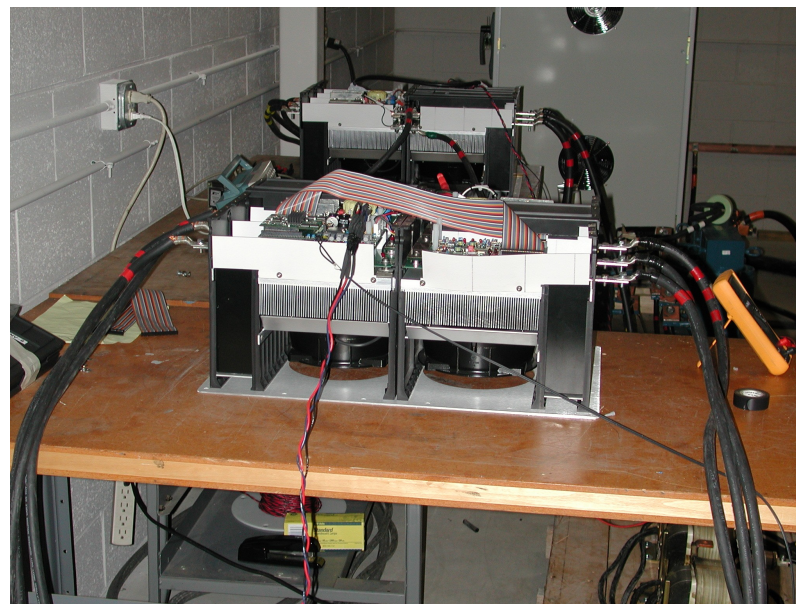
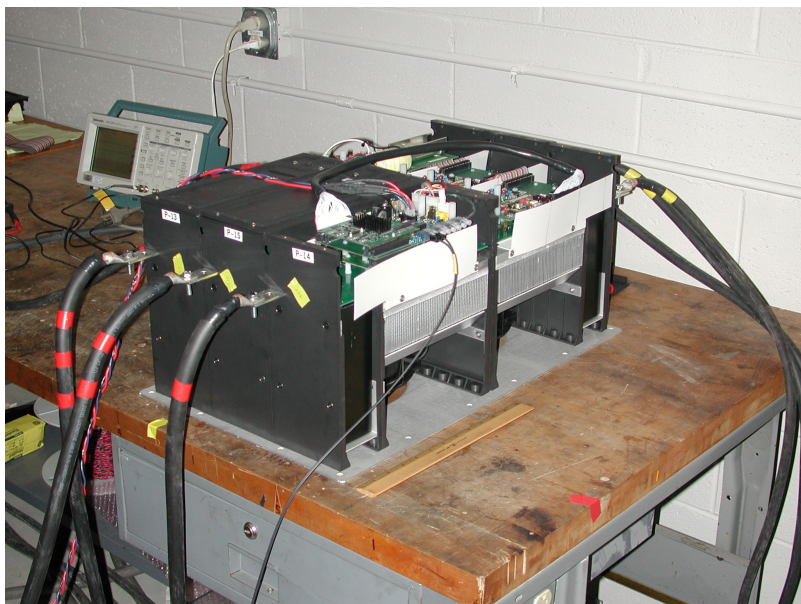
System Power Schematic

Power Electronic Systems



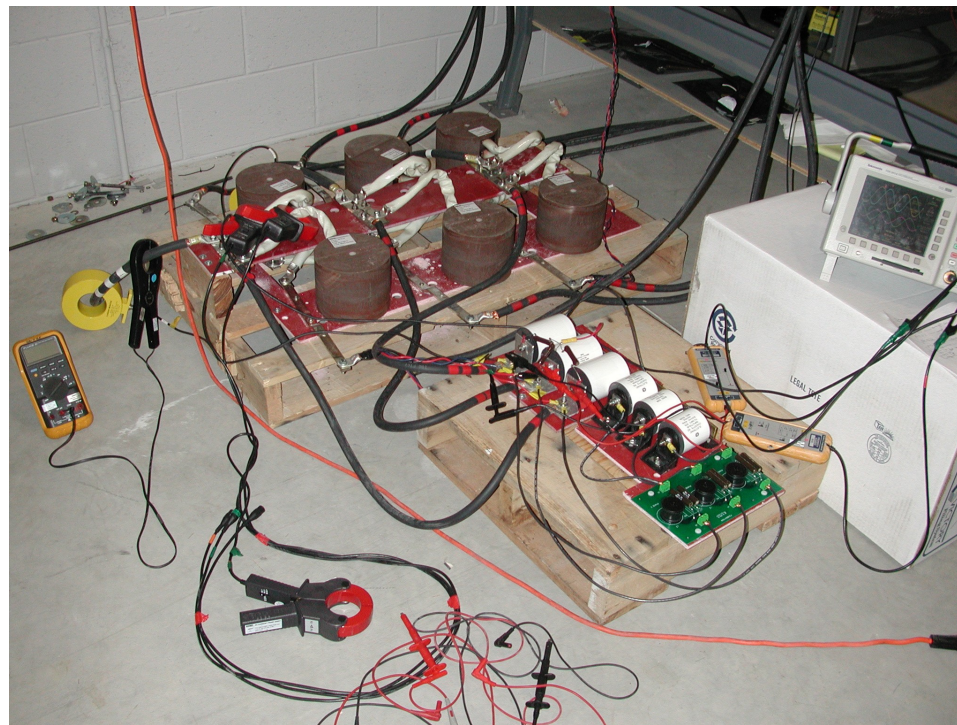
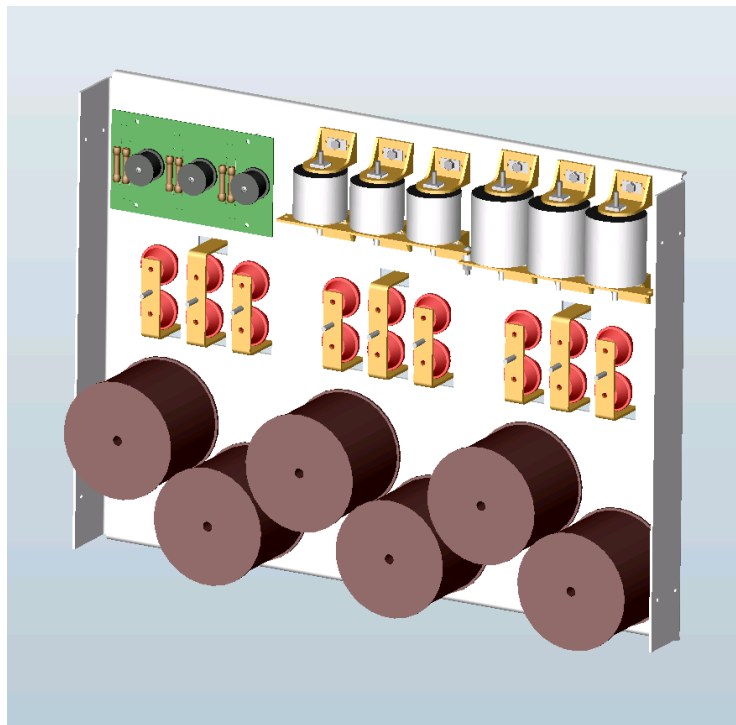
PEBB Test Units

Power Electronic Systems



UPS Output Filter

Power Electronic Systems



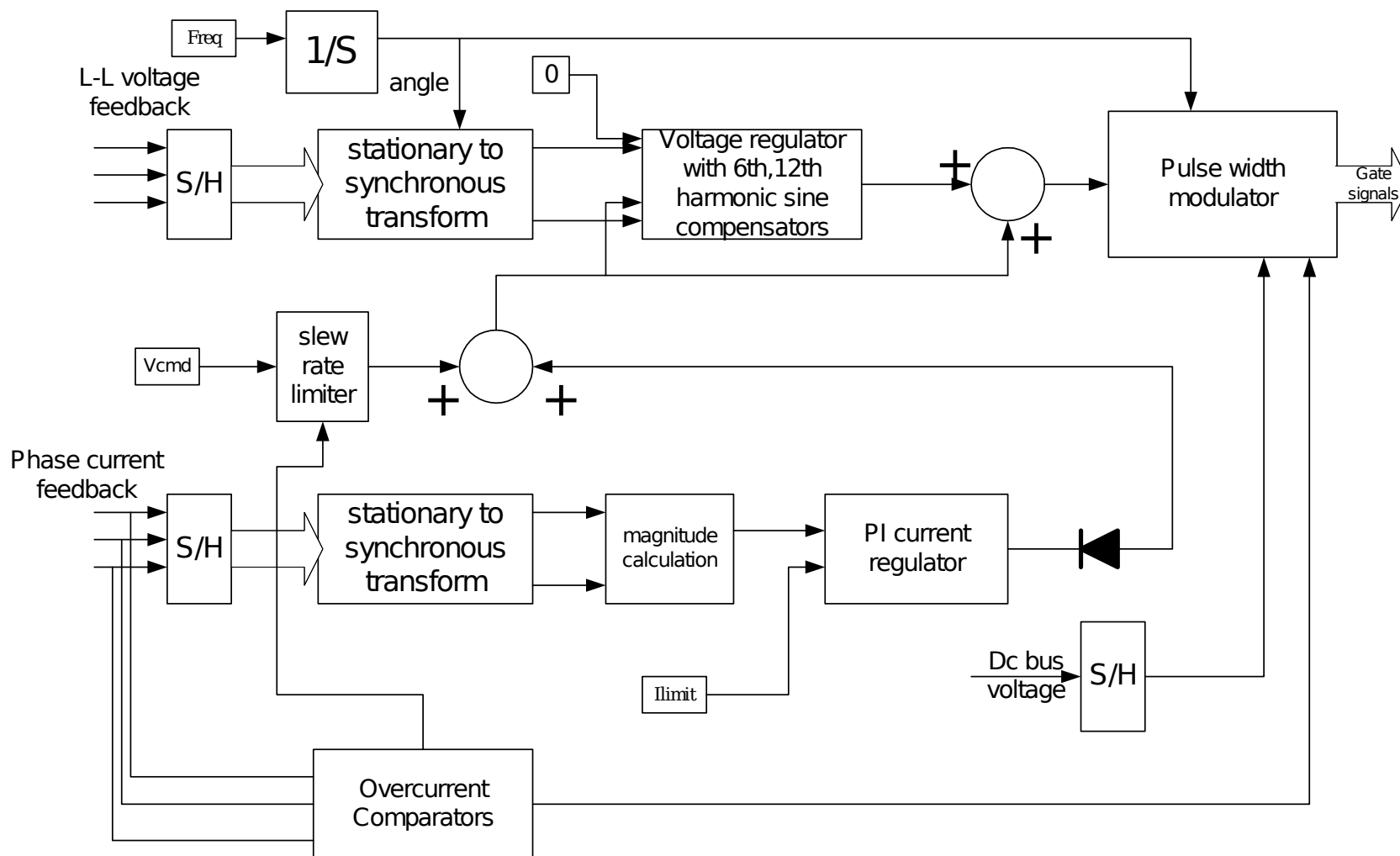
UPS Control Algorithm

Power Electronic Systems

- Synchronous reference frame voltage regulators with 6th, 12th harmonic regulators
- Outer current limit loop
- Pulse by pulse current limit reduces output voltage and starts rebuild to current limit level
- Space vector modulation strategy with 8 kHz interleaved gating of 6 inverter poles

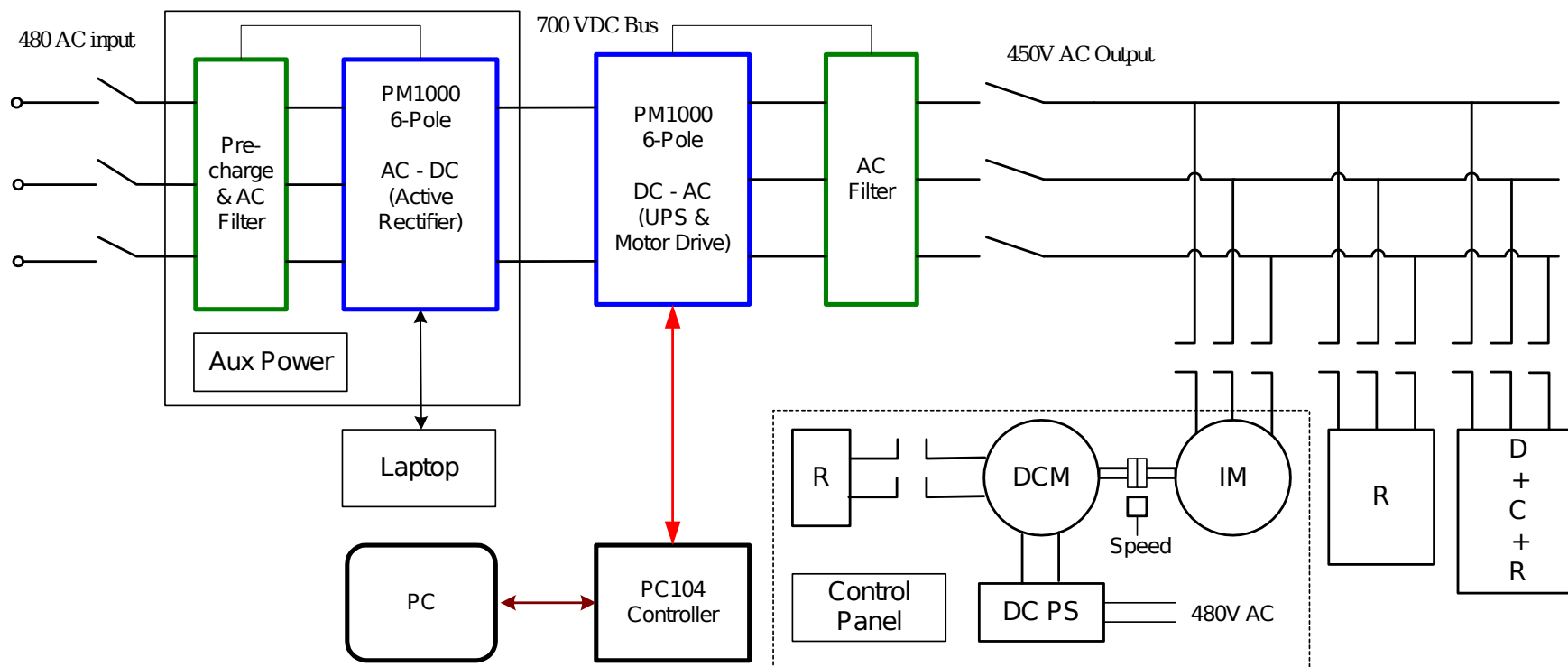
UPS Control Algorithm

Power Electronic Systems



UPS Test Configuration

Power Electronic Systems



UPS Mode Tests Performed

Power Electronic Systems

- Full Load
 - Waveform Quality
 - Thermal Performance
- Unbalanced Load
- Non-Linear Load
- Load Step Response
- Current Limit Response
- Short Circuit Performance

Full Load Waveform Quality

Power Electronic Systems

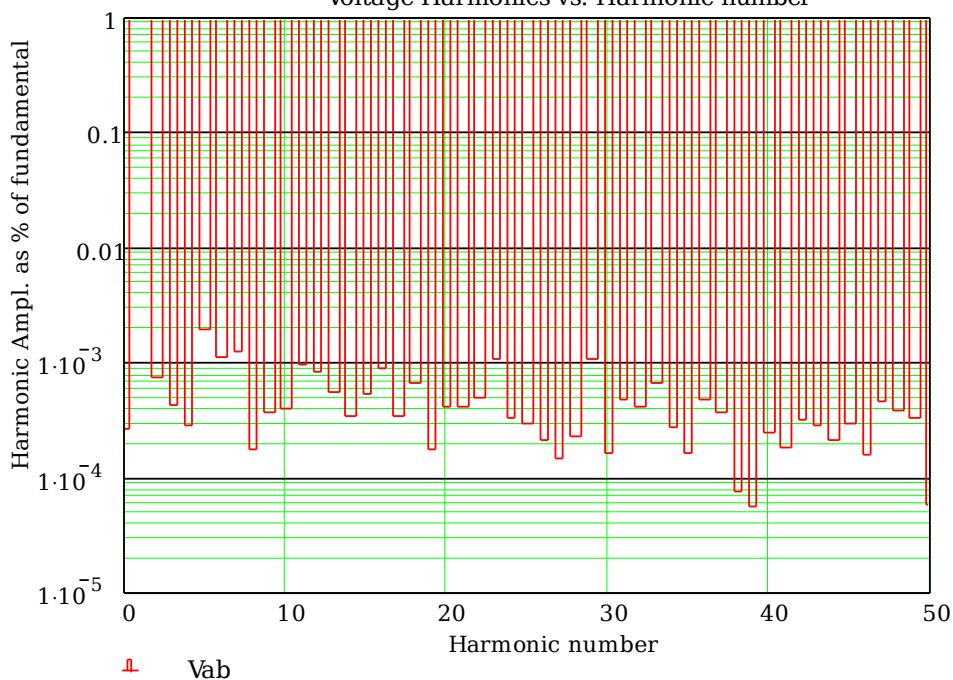
$V_{rms} = 443.70V$

$I_{rms} = 287.17A$

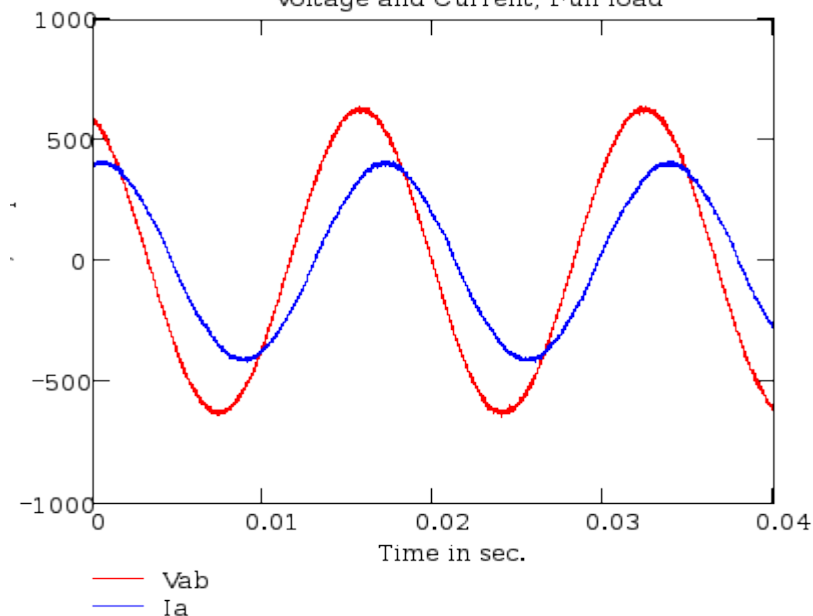
THDv = 2.03%

THDi = 2.91%

Voltage Harmonics vs. Harmonic number



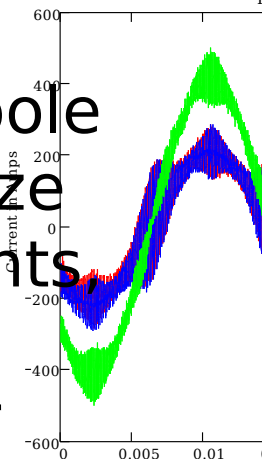
Voltage and Current, Full load



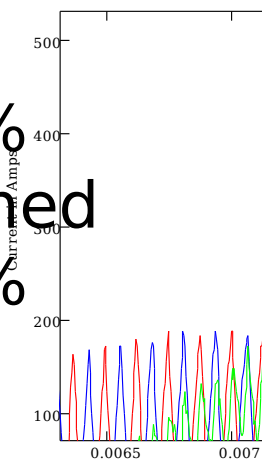
Interleaved Inverter Currents

Power Electronic Systems

Interleaved individual pole currents sum to minimize carrier frequency currents, leaving predominant harmonics at 2X carrier

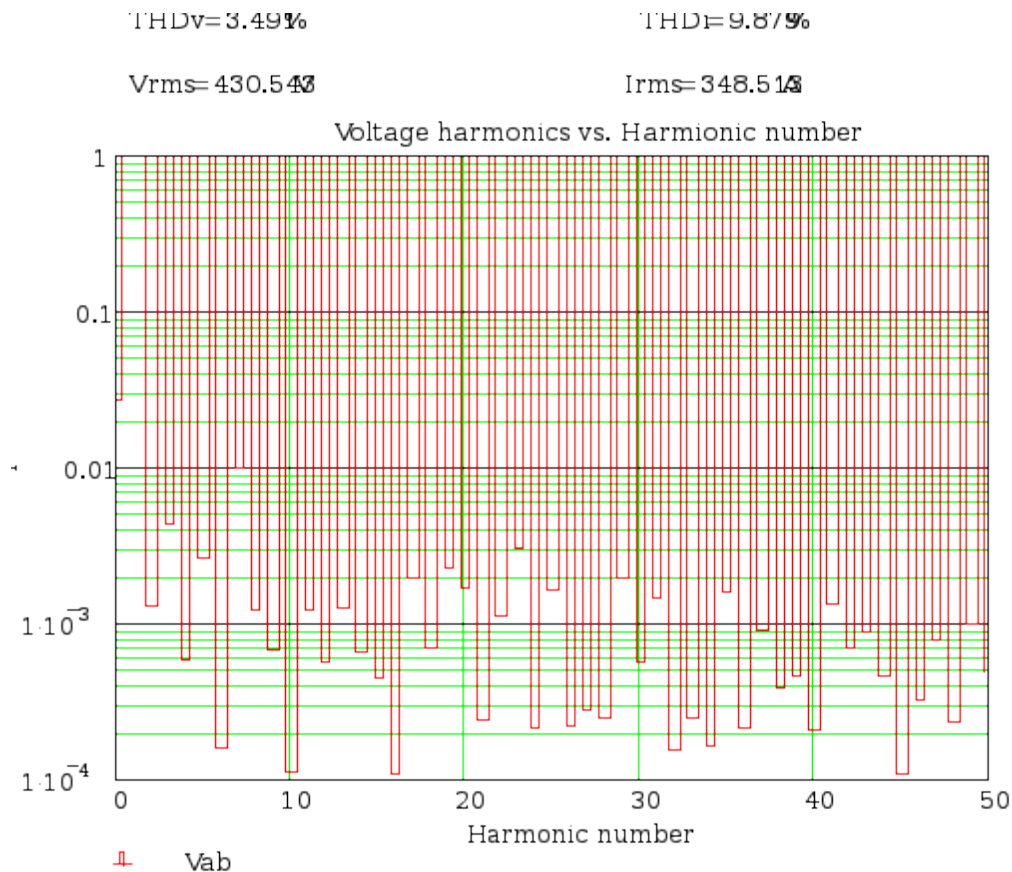


ITHD of pole current is 35%
ITHD of summed current is 10%



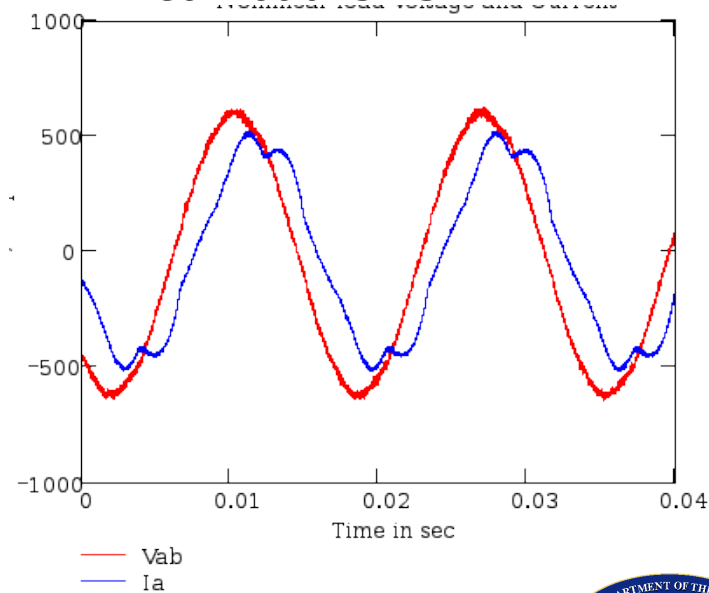
Nonlinear Load

Power Electronic Systems



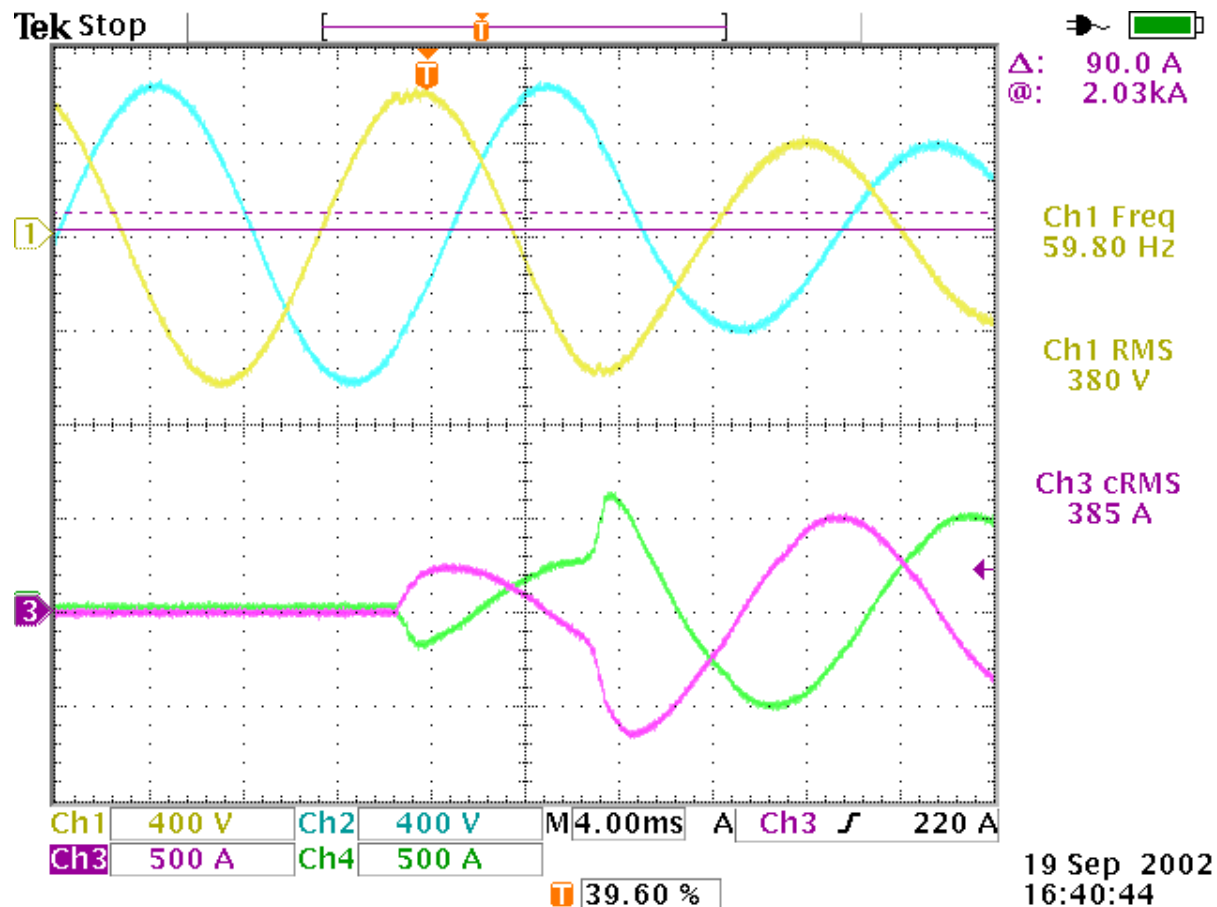
UPS voltage regulators
Compensate for
5th, 7th, 11th,
13th harmonics.

Nonlinear load is about 70
kW
Linear load is 234 kW



Current Limit Response

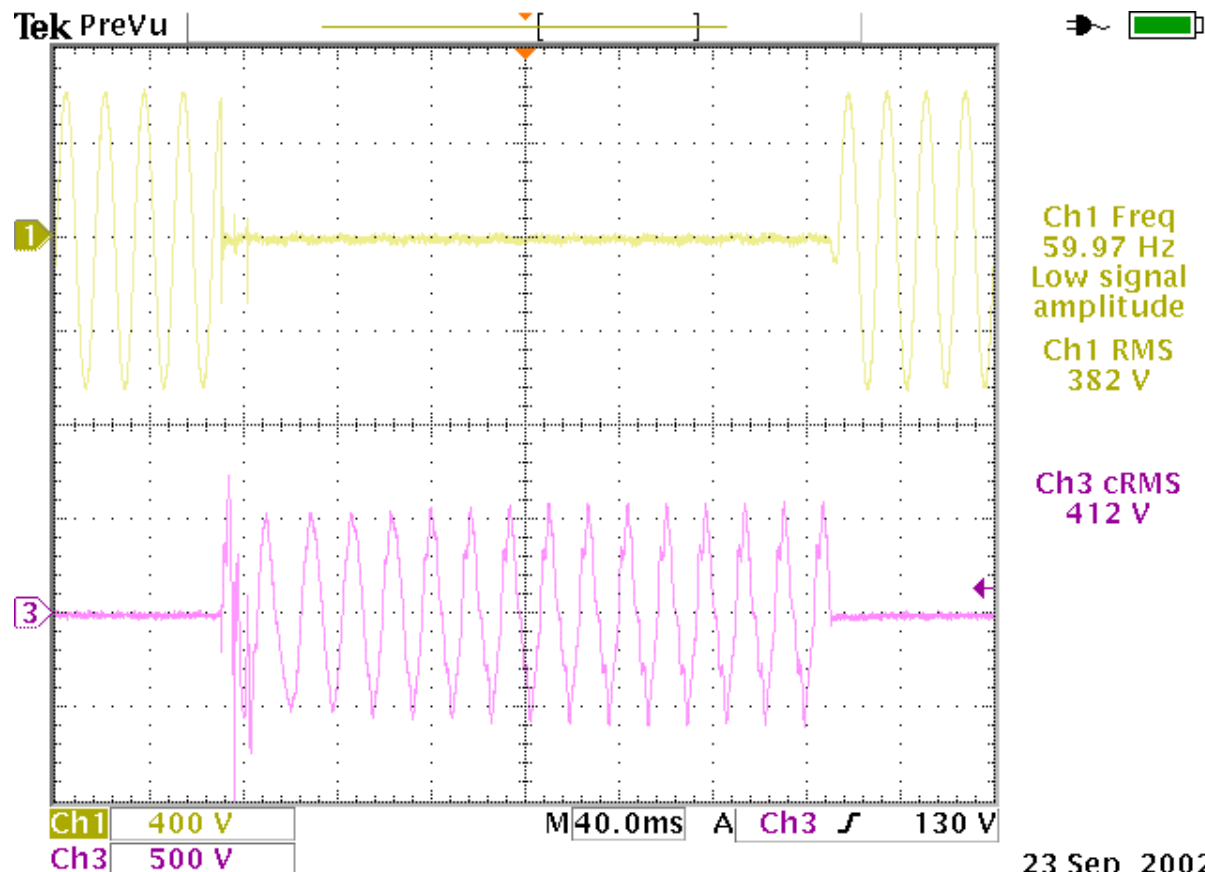
Power Electronic Systems



- Load Step:
Zero to
500kW
- Trace 1: Vab
- Trace 2: Vbc
- 400 V/div
- Trace 3: Ia
- Trace 4: Ib
- 500 A/div

Short Circuit Recovery

Power Electronic Systems



- 3 Phase Short with No Load
- Trace 1: Vab
 - 400 V/div
- Trace 2: Ia
 - 500 A/div

23 Sep 2002
17:36:08

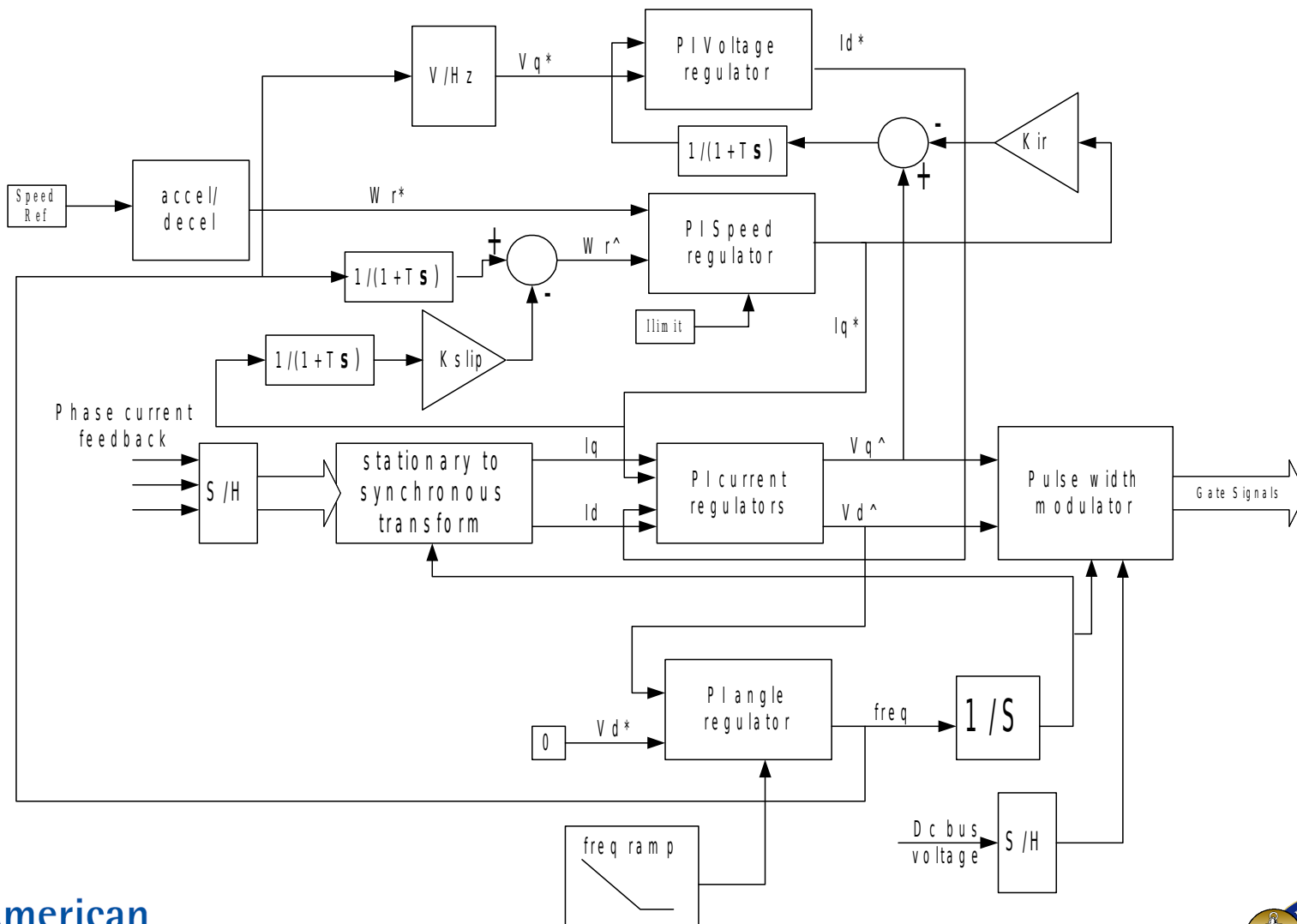
Motor Drive Control Algorithm

Power Electronic Systems

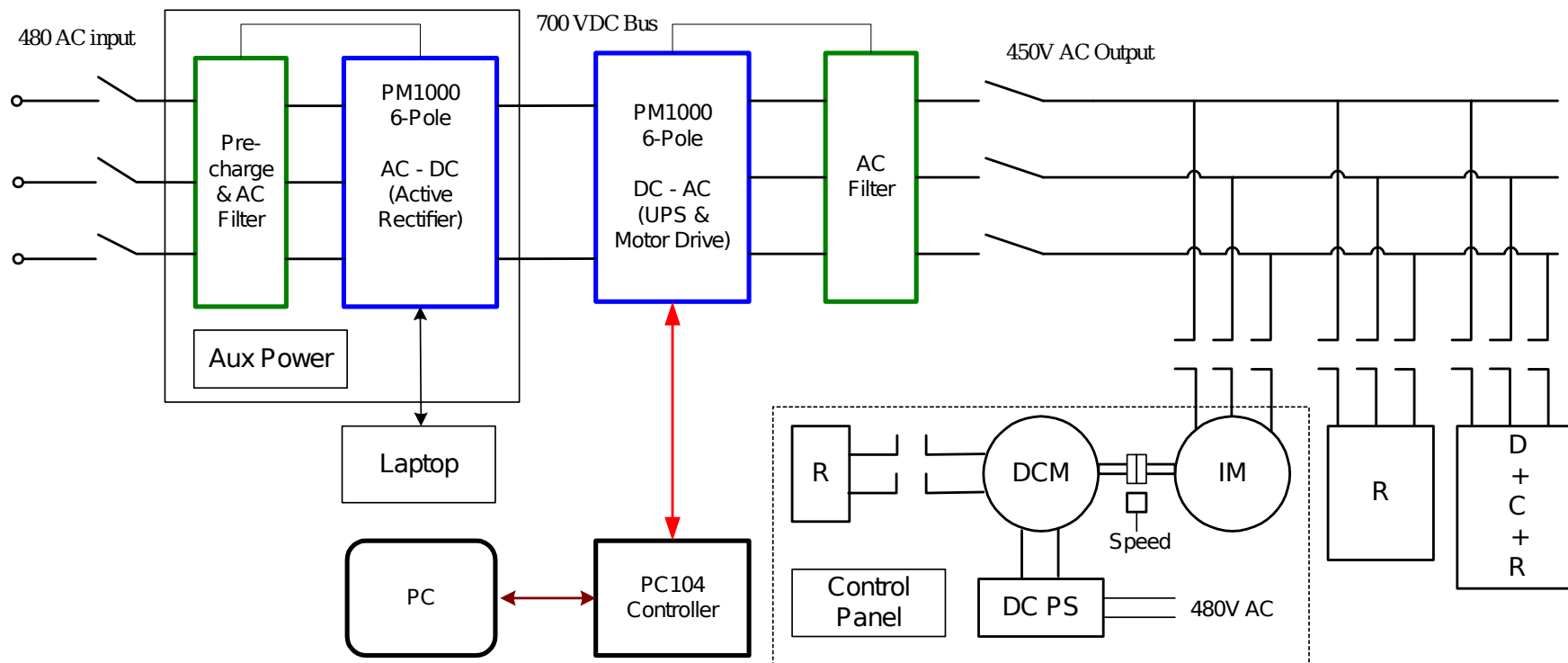
- Stator flux oriented control
- Multiple control loop topology is parameter insensitive
- IR comp and Slip comp adjustments like V/Hz drives
- Bumpless rotating start algorithm to catch a spinning motor

Motor Drive Control Algorithm

Power Electronic Systems



Power Electronic Systems



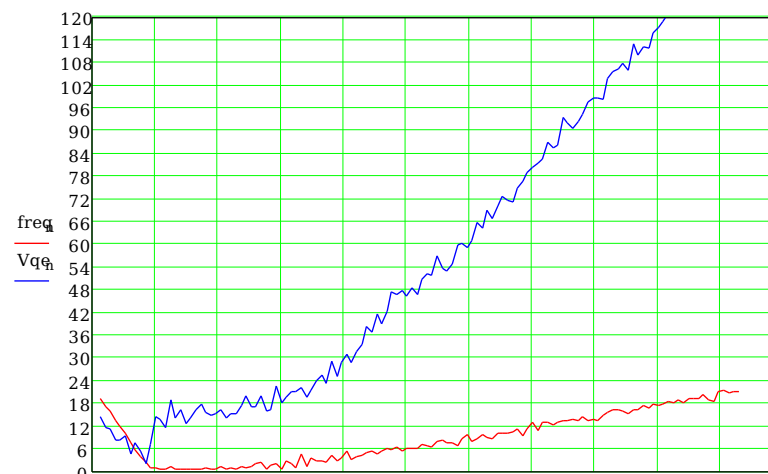
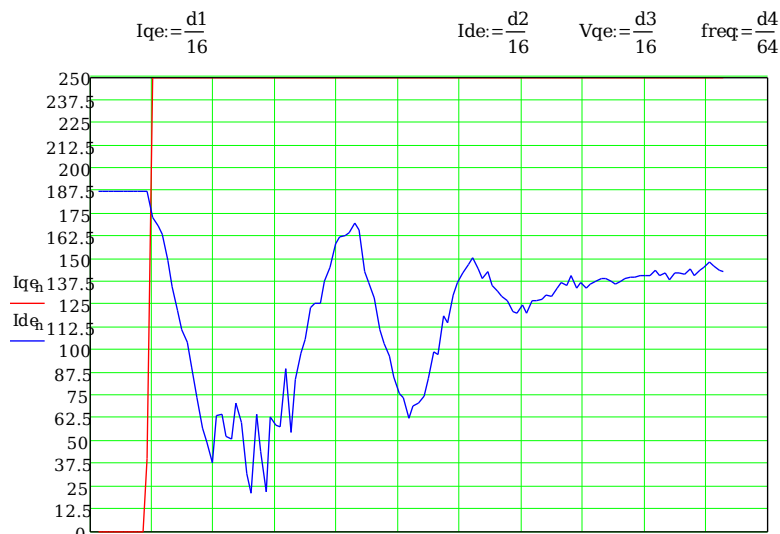
Drive Mode Tests Performed

Power Electronic Systems

- Starting from Stall
- Speed Step Response
- Field Weakened Operation
- “Bumpless” Start of Rotating Motor

Motor Drive - Starting from Stall

Power Electronic Systems

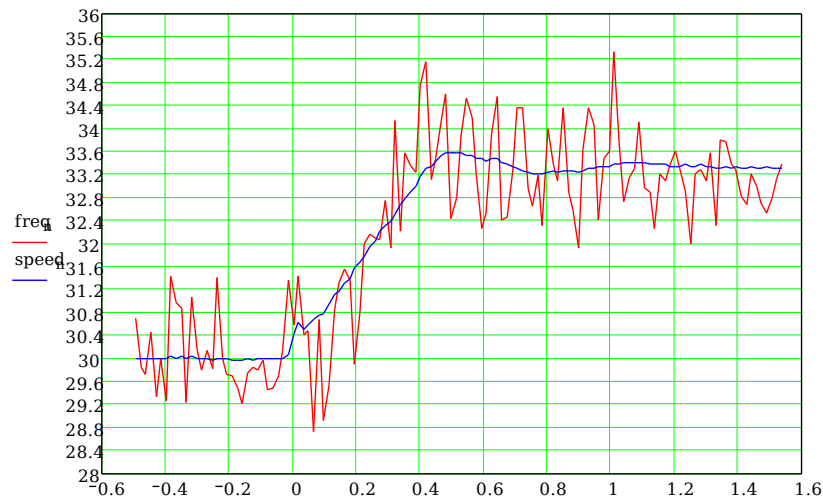
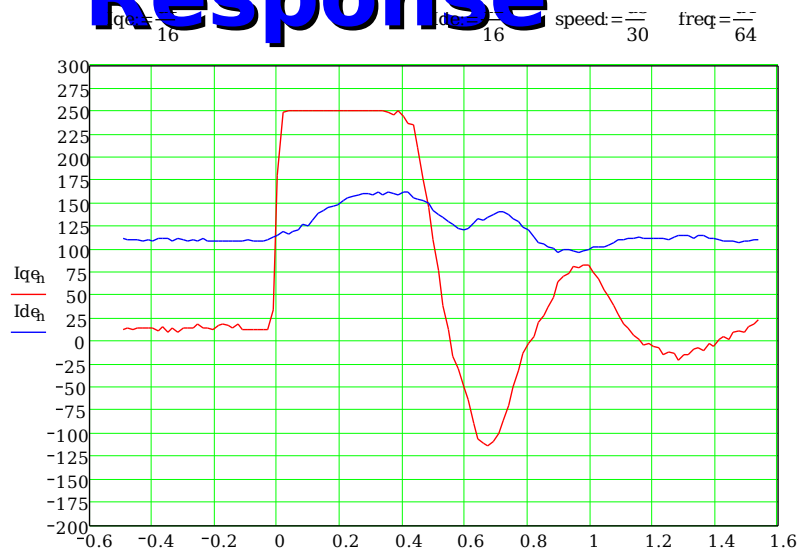


Frequency reduced in one second from 60 Hz to 0.5 Hz

- Lock obtained when Voltage regulator (I_{de}^* comes out of current limit)
- When lock is observed, speed regulator is released, producing I_{qe}^*
- Acceleration begins, and voltage regulator settles to proper I_{de}

Motor Drive - Step Speed Response

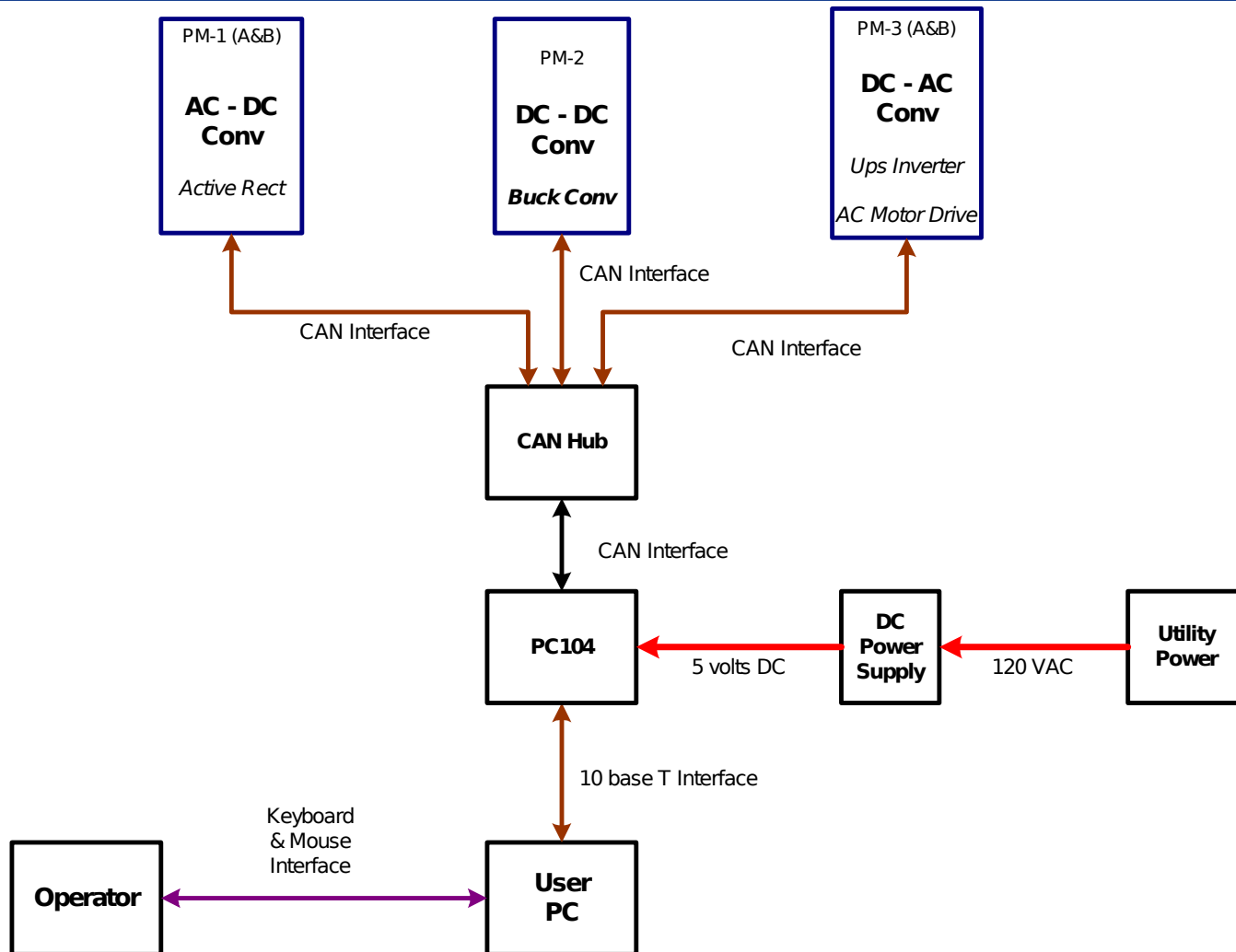
Power Electronic Systems



900 to 1,000 RPM step speed reference change
Speed is simply filtered frequency

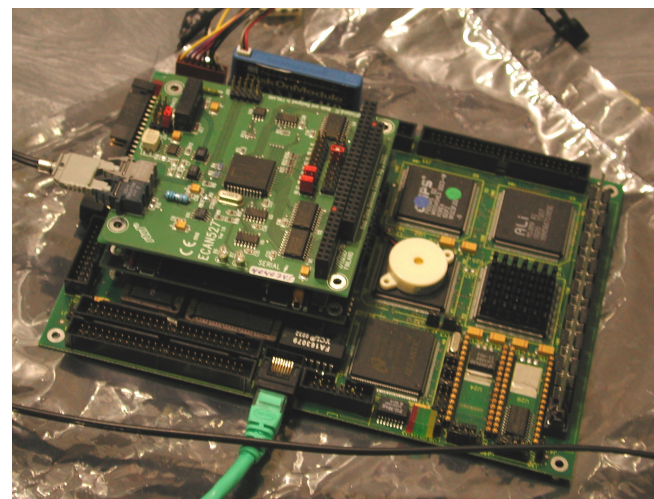
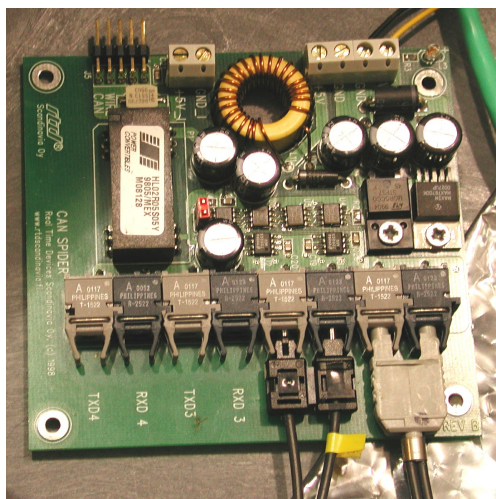
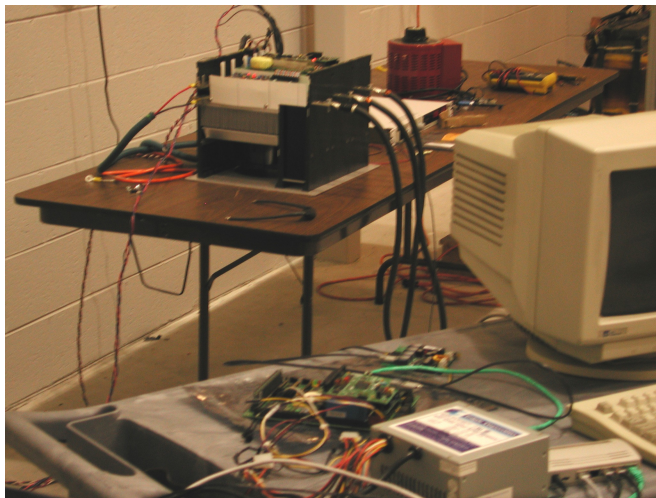
PC104 Interface Diagram

Power Electronic Systems



PC104 Hardware

Power Electronic Systems



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Controller Features

Power Electronic Systems

- Hard Real Time Operating System (RTAI/RTLinux)
- Variety of communication capabilities
- Full PC Compatibility/Upgradeability/Programmability
- Compact Form Factor/Rugged (industrialized)

Controller Functions

Power Electronic Systems

- System Controller that controls all PowerModules
- Operates system state machine
- External communication via internet Protocol (UDP/IP)
- Modular Software allows command line configurability of system timing, task priorities and buffer sizes.
- GUI Software
 - System Control via User Commands
 - Display metered parameters
 - Change User settable parameters (setpoints, gains, etc)
 - Detailed fault history (time stamped)
 - Real time warnings

System Communication

Power Electronic Systems

- PC104 System I/O capability
 - Inherent to PC104 PCB (with no cards)
 - 10 Base-T Ethernet (10 MB)
 - 48 Digital IO – bi-directional
 - 4 serial ports (4 – RS232, 2 config to RS485)
 - 1 parallel port
 - Add on Cards
 - CAN fiber optic or galvanic (1 MB)

HMI Display - System Control UPS Operating

Power Electronic Systems

PM1000 Diagnostic Interface Software (PM 1000 Configuration Management)

Start Connected on address 192.168.0.22

System Control User Params Parameter Properties Logs Fault Log End around device control

System Idle	Precharge Efficiency	CLOSED DISABLED		
Active Rect	L-L Voltage Phase A Curr		Output Pwr DC Bus Volt	
DC/DC/Conv	DC V Out DC Curr Out		Output Pwr	
Motor Drive	L-L Voltage Phase A Curr		Output Pwr Frequency	Speed
UPS Control	L-L Voltage Phase A Curr	36.9375 1.5	Output Pwr Frequency	Power Factor 0 ☒ Converter On



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HMI Display - System Control

Fault

Power Electronic Systems

PM1000 Diagnostic Interface Software (PM 1000 Configuration Management)

Start Connected on address 192.168.0.22

System Control | User Params | Parameter Properties | Logs | Fault Log | End around device control

System Idle	Precharge	CLOSED		
	Efficiency	DISABLED		
Active Rect	L-L Voltage		Output Pwr	
	Phase A Curr		DC Bus Volt	
DC/DC/Conv	DC V Out		Output Pwr	
	DC Curr Out			
Motor Drive	L-L Voltage		Output Pwr	
	Phase A Curr		Frequency	
			Speed	
UPS Control	L-L Voltage	36.875	Output Pwr	0
	Phase A Curr	0.9375	Frequency	60
			Power Factor	0
			☒ Converter On	

Faulted Last Fault Converter lost connection - 2

Go to Fault Log

Hard Reset

Leveled Reset



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HMI Display - System Control Fault Reset

Power Electronic Systems

PM1000 Diagnostic Interface Software (PM 1000 Configuration Management)

Start Connected on address 192.168.0.22

System Control User Params Parameter Properties Logs Fault Log End around device control

System Idle	Precharge	CLOSED		
	Efficiency	DISABLED		
Active Rect	L-L Voltage		Output Pwr	
	Phase A Curr		DC Bus Volt	
DC/DC/Conv	DC V Out		Output Pwr	
	DC Curr Out			
Motor Drive	L-L Voltage		Output Pwr	
	Phase A Curr		Frequency	
			Speed	
UPS Control	L-L Voltage	36.875	Output Pwr	0
	Phase A Curr	0.9375	Frequency	60
			Power Factor	0
			☒ Converter On	

Reset Last Requested Run Level



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HMI Display - Set Points

Power Electronic Systems

PM1000 Diagnostic Interface Software (PM 1000 Configuration Management)

Start Connected on address 192.168.0.22

System Control User Params Parameter Properties Logs Fault Log End around device control

☒ Initiate Autoupdates Get Param Table

Description	Requested	Value
UPS Frequency Set Point	60	655
AC RMS Voltage Line to Line Out Setpoint	14	14
Proportion Gain on Voltage Regulator	1520	1520
Integral Gain on Voltage Regulator		-1520

Read Param Write Param Read All <-Back



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HMI Display - Metered Parameters

Power Electronic Systems

PM1000 Diagnostic Interface Software (PM 1000 Configuration Management)

Start Connected on address 192.168.0.22

System Control User Params Parameter Properties Logs Fault Log End around device control

☒ Initiate Autoupdates Get Param Table

Description	Update	Value
Phase A RMS Current	True	1.000
Phase B RMS Current	True	1.375
Phase C RMS Current	True	.625
Positive Sequence RMS Current	True	.063
Negative Sequence RMS Current	True	.063
Phase A-B Line to Line RMS V	True	36.813
Phase B-C Line to Line RMS V	True	36.875
Phase C-A Line to Line RMS V	True	36.813
Positive Sequence RMS Voltage	True	21.250
Negative Sequence RMS Voltage	True	.000
Inverter Frequency	True	60.000
Output Power	True	.000
Inverter Efficiency (Disabled)	True	.000
Output KVA	True	.003
Output Power Factor	True	.000
Total Harmonic Distortion of Input Current	False	32767.000
Total Harmonic Distortion of Input Voltage	False	2513.000
PCB Temperature	False	35.000
UPS DSP A System Mode	False	6.000
UPS DSP A Source of Reset	False	3.000
UPS DSP A PLL State	False	.000

Read Param Write Param Read All <--Back



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HMI Display - Fault Log

Power Electronic Systems

PM1000 Diagnostic Interface Software (PM 1000 Configuration Management)

Start Connected on address 192.168.0.22

System Control User Params Parameter Properties Logs **Fault Log** End around device control

Time	Class	Trigger ?	Description
09/23/2002 10:07:54	0	True	device_id=1
09/23/2002 11:08:21	3	False	Converter lost connection - 1
09/23/2002 11:08:21	3	False	Converter lost connection - 2
09/23/2002 13:24:33	0	True	device_id=1
09/23/2002 13:24:34	0	False	device_id=1

Back to Sys Control

Active Rectifier Control Algorithm

Power Electronic Systems

- Synchronous reference frame current regulators and DC bus voltage regulator working – Tested to 250 kW.
- Phase locked loop synchronization to AC line voltage working.
- Current harmonics can be reduced together with better control of DC component of line current.

DC-DC Converter Control Algorithm

Power Electronic Systems

- 3 phase interleaved, 2 quadrant control developed.
- Inner current loop control with one phase executing every $56 \mu\text{s}$ written in C.
- Synchronized current sampling to reject ripple component.
- PWM signals from DSP drive gating state machines in the CPLD to obtain proper interleaved operation.

UPS / Drive with SiC based Module

Power Electronic Systems

- Control modifications for higher switching frequency (20 – 30 kHz)
 - Keep control algorithms running at no more than 8 kHz rate – requires additional state logic in software and/or CPLD
 - Update commanded voltage angle for every PWM carrier cycle
 - May need dead time (anti-overlap) compensation
 - May need current sharing algorithm with paralleled poles

PEBB 3-Pole PowerModule

Power Electronic Systems



Relative Size



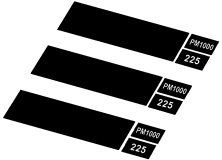
Figures of Merit

Power Rating	200 kW	200 kW	160 kW
Output Current @ 50°C			
Rated	240A	240A	139A
Continuous w/o	300A	264A	187A
overload	360A	360A	209A
Overload (1 min.)	480A	No	278A
Overload (200%)	2,300 in³	4,315 in ³	7,080 in ³
Size	55 lbs	121 lbs	139 lbs
Weight	87 W/in³	28 W/in ³	23 W/in ³
Power Density	High Speed	Medium Speed	High Speed
Communications	Multiple	Single	Multiple
Protocol	Fiber Optic	Wire	Wire
Link	Yes	No	No
Isolation	Internal or	No	External
Optional Modules	External		

PM1000 Sales Sheet

Power Electronic Systems

PowerModule™ PM1000



PRO Sheet

Be a PRO on PROVIDing PROduct information.

The PM1000 topology includes proprietary and patent pending design techniques that cleverly integrate power electronics technology, real-time control strategy and communication protocol in a common and standard component unit called the Power Pole. The assembly of several power poles allows for the configuration of different PM1000 PowerModules that are applied to a wide range applications such as AC-AC, AC-DC, DC-DC or DC-AC. A PM1000 power converter can include from three to eight power poles. Several PM1000 power converters can be configured in series and/or parallel to build higher voltage and power rated converters.

All the communications between the PM1000 and the remote devices, or controller, are handled through a fiber optic link that provides high noise immunity. A hardware interface board is available to convert fiber optic signals to a serial format. Our standard communication protocols for the PM1000 include RS-232 and CAN. Other protocols are supported via a PC-104.

High Power Density

- Up to 8 W/cm³

Scalable Design

- Standard building blocks
- Bi-directional functionality
- Fully programmable

Flexible Architecture

- Expandable configuration
- Fully integrated

Self-Supportive

- Fault annunciation
- Product protection against malfunction
- Easy troubleshooting

Value Proposition

PowerModule™ PM1000

PRO Sheet

•Modular Design

- Pole Based (combine 3 – 8 poles)
- Pole Interoperability

•Re-Programmable

- 1 unit does multi-functions
- Programming can be done remotely

•Easy to Use

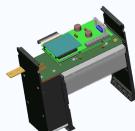
- Graphical User Interface (GUI)
- Remote Communication (wireless)
- Self-Protected
- Connect-And-Go™

Key point here is the ability to combine 3 to 8 power poles of the same or different ratings into a PowerModule. This allows the PowerModule to perform multiple tasks at different power levels.

Key point here is the ability to have a PowerModule switch from one application to another. The PowerModules are bi-directional and can be used to start a motor and then act as an active rectifier as in a UPS. Another example being a PowerModule which is acting as a motor drive can be reprogrammed to be an active filter and again reprogrammed to be a DC-DC converter without changing the PowerModule hardware. This flexibility translates into reduced inventory of inverters needed for multiple, different applications.

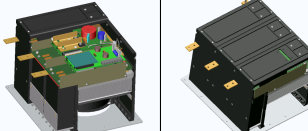
Key points here are the PowerModule is user friendly (GUI), easily accessed (remote communication) and intelligent (self-protected). The PowerModule can be re-programmed remotely to change operation or update software.

Power Pole



Combine 3 - 8 Power Poles to create a PowerModule

PowerModule (3-poles)



PowerModule Block Diagram



Power Electronic Systems
15775 W. Schaefer Court
New Berlin, WI 53151
Phone: 1.262.901.6000 Fax: 1.262.901.0100

PEBB MV Project

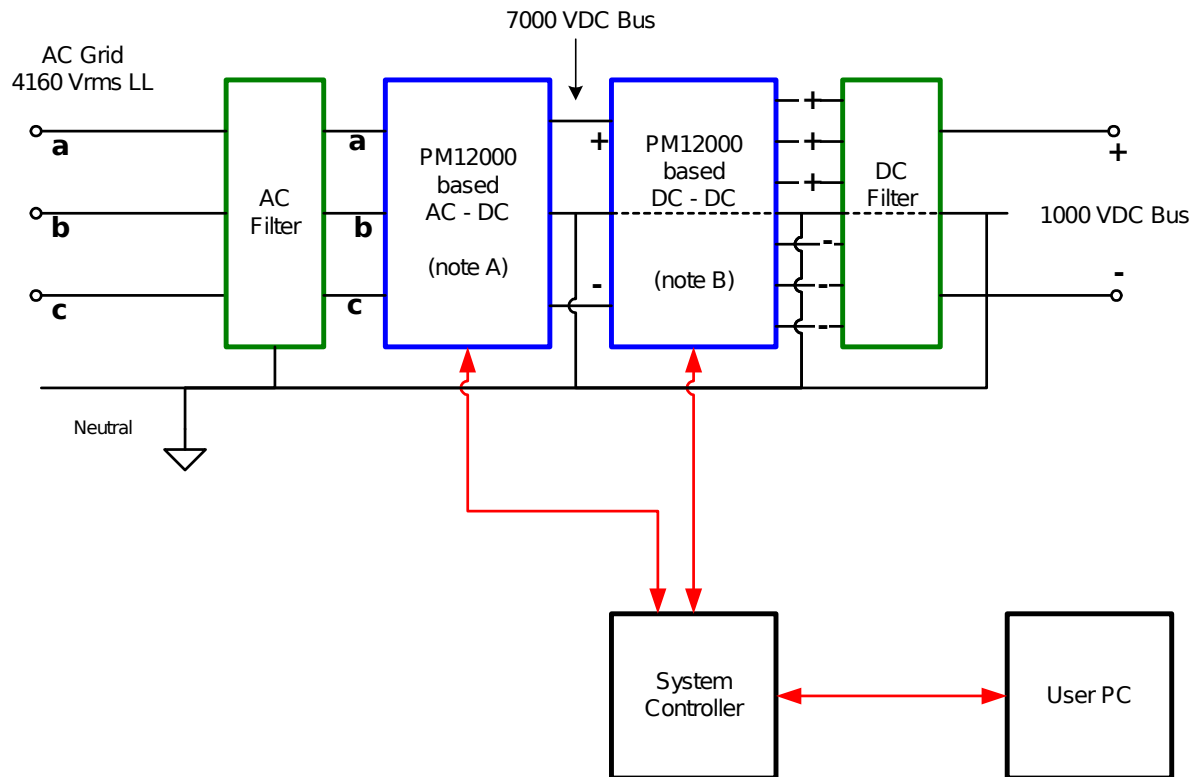
Power Electronic Systems

Mission

- To develop a medium voltage AC-DC converter system using a power electronic building block format to meet the specifications of the PEBB contract. The medium voltage power pole will be the foundation of a medium power converter product for AMSC.
- The system will include:
 - 3 phase AC-DC Converter ($4,160V_{AC}$ - $7,000V_{DC}$)
 - 3 pole DC-DC Buck Converter ($7,000V_{DC}$ - $1,000V_{DC}$)
 - PC104 based System Controller

PEBB MV System

Power Electronic Systems



Note A

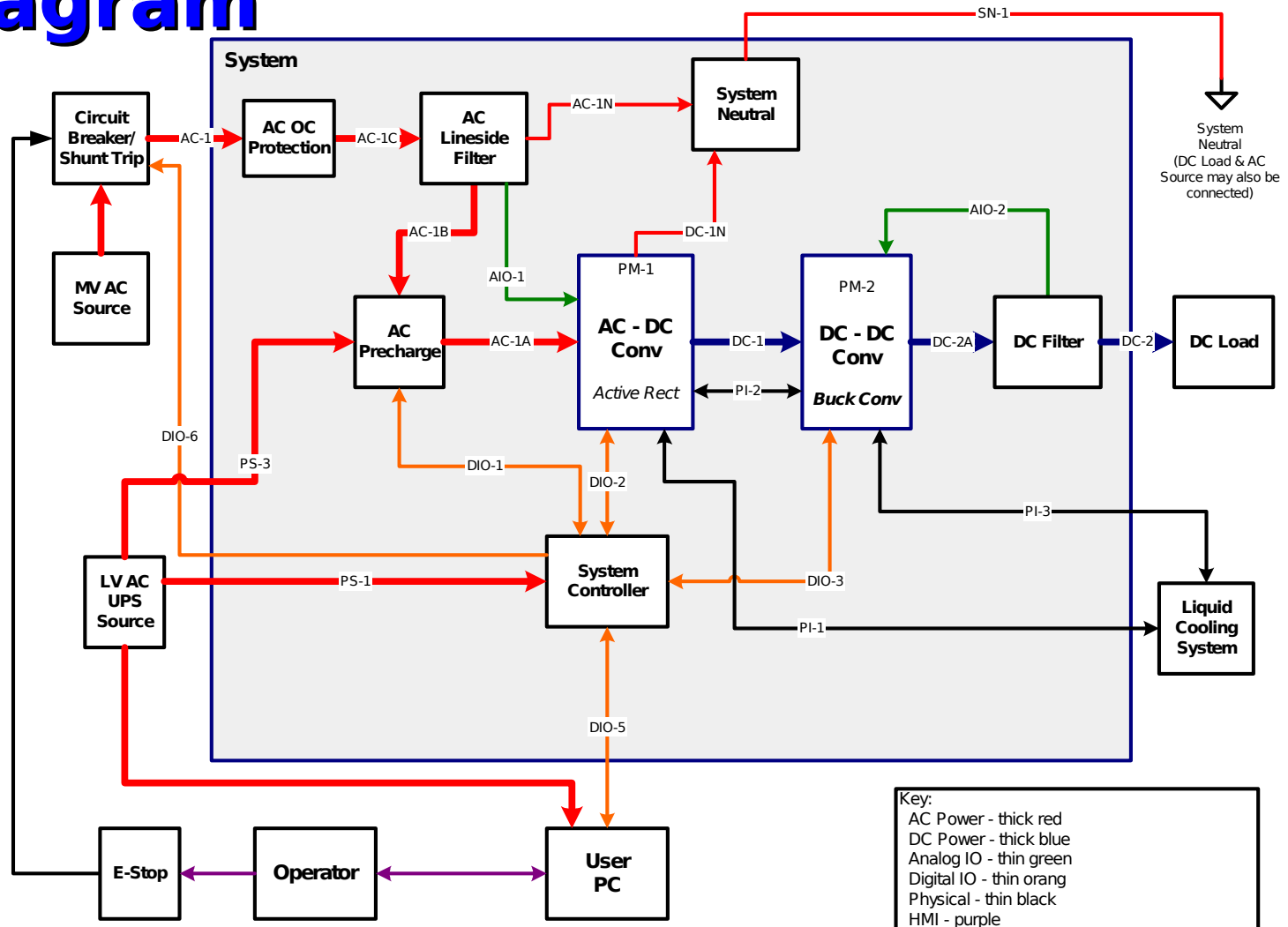
- 1) Uses 3 PM12000 poles
- 2) PM12000 is a single pole (3 level topology)
- 3) Active rectifier operation

Note B

- 1) Uses 3 PM12000 poles
- 2) PM12000 is a single pole (3 Level topology)
- 3) Bidirectional DC to DC operation
- 4) 3 pole interleaved PWM design

PEBB MV System Interface Diagram

Power Electronic Systems



Key:
AC Power - thick red
DC Power - thick blue
Analog IO - thin green
Digital IO - thin orange
Physical - thin black
HMI - purple
(arrows indicate primary direction of signal flow)

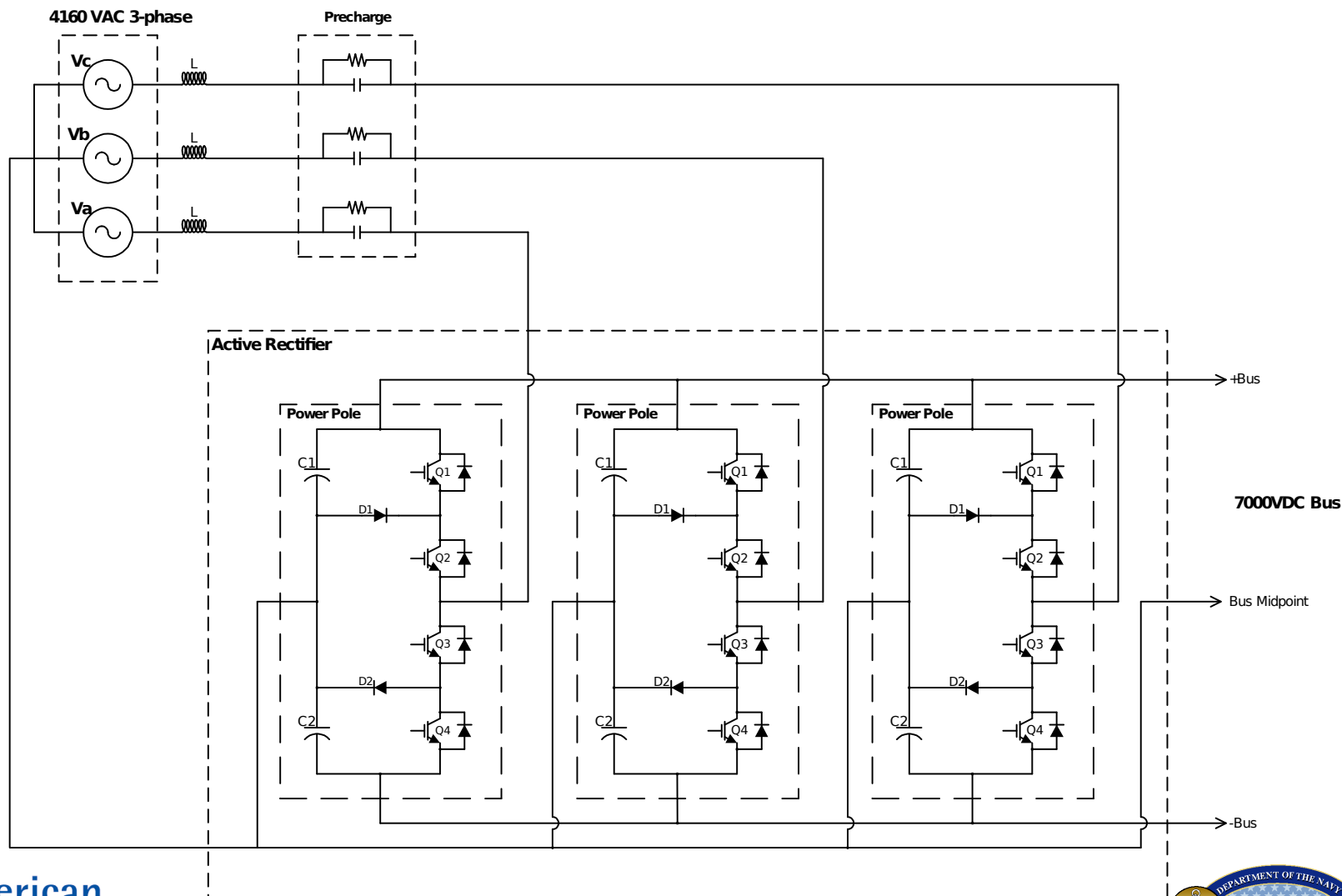
PEBB MV System Features

Power Electronic Systems

- MV power pole based upon a Neutral Point Clamped 3 level converter
- All power poles will be liquid cooled
- AC-DC Converter operates as an active rectifier
- DC-DC buck will employ interleaved PWM - lower harmonics
- PC104 System Controller will provide for control and monitoring of system
- System will utilize PEBB LV control software, control PCB, and PC104 controller

MV Active Rectifier Circuit

Power Electronic Systems



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AC-DC Rectifier Performance AC Bus Specs

Power Electronic Systems

Parameter	Units	Value	Constraint	Comments
Power - <i>Rated</i>	kW	2000	Controlled	
KVA - <i>Rated</i>	kVA	2000	Controlled	
Connection		4 wire	Controlled	Neutral connection optional
PWM Frequency	kHz	1	Controlled	
Power factor		1.00	Controlled	+ lead - lag
Frequency Specs:				
<i>Nominal</i>	Hz	60 Hz	Util Grid	
<i>Transient Regulation</i>	%	2	Util Grid	Transients under 100 ms
<i>Steady State Regulation</i>	%	10	Util Grid	Steady state
Voltage Specs:				
<i>Nominal (L-L)</i>	Vrms	4160	Util Grid	
<i>Regulation - Steady state</i>	%	+/- 10	Util Grid	
<i>Distortion THD</i>	%	5	Util Grid	See IEEE 519 for limits on individual harmonics
<i>Maximum Unbal - Neg.</i>				

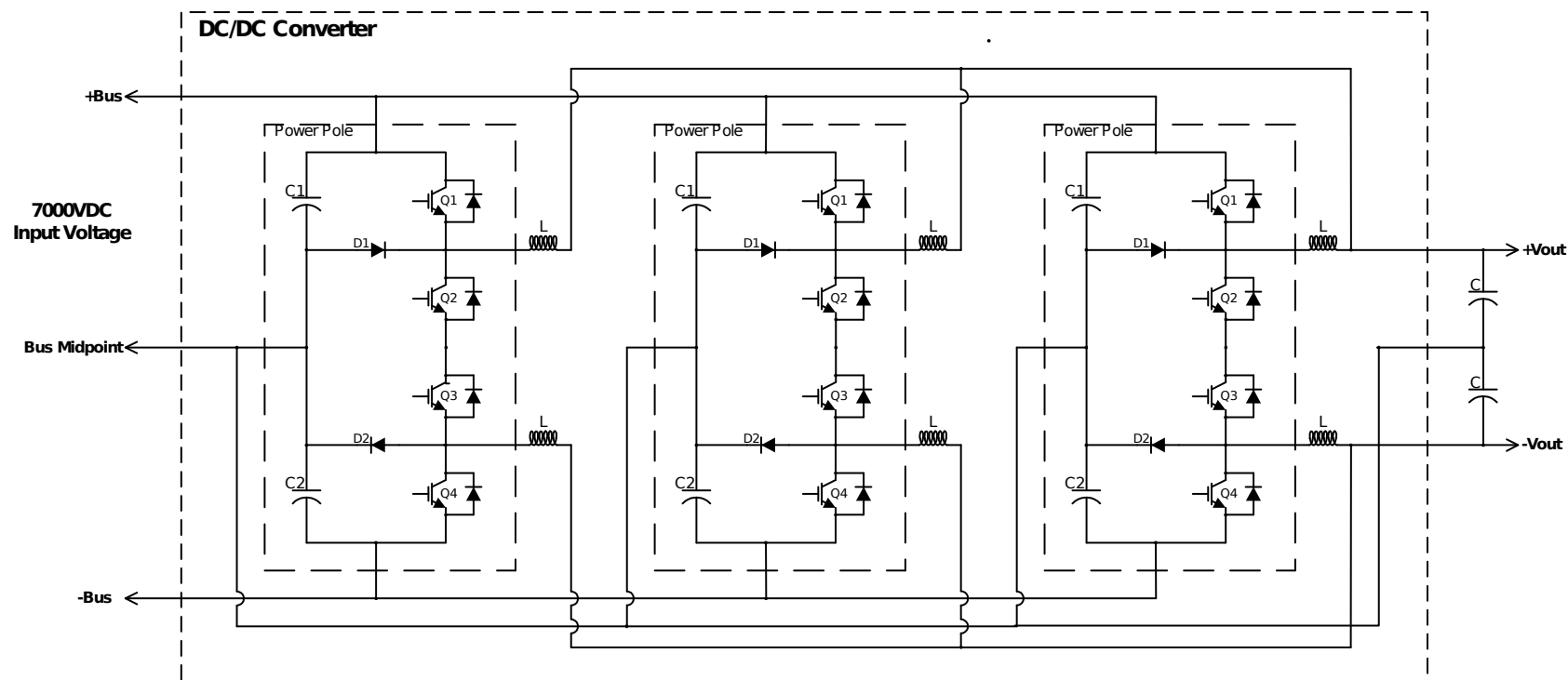
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MV DC-DC Converter Circuit

Power Electronic Systems



DC-DC Converter Performance

Specs

Power Electronic Systems

Parameter	Units	Value	Constraint	Comments
Power - <i>Nominal</i>	kW	1000	Result	at nominal voltage
Connection	wires	7	Controlled	+DC Bus(3), - DC Bus(3), DC Bus midpoint(1)
DC Bus Voltage Specs:				
<i>Nominal</i>	volts	1000	Controlled	
Regulation - <i>Steady state</i>	%	+/- 2.0	Controlled	
Regulation - <i>Transient</i>	%	+/-10.0	Controlled	0-100% step load
Regulation - <i>Recovery</i>	sec	0.1	Controlled	
<i>Maximum Output Setting</i>	volts	6000	Controlled	User adjustable
<i>Minimum Output Setting</i>	volts	700	Controlled	User adjustable
<i>Maximum Ramp Rate</i>	volts/sec	3000	Controlled	
<i>Minimum Ramp Rate</i>	volts/sec	2	Controlled	
<i>Maximum Voltage Ripple</i>	%	1	Controlled	peak to peak, for nominal conditions

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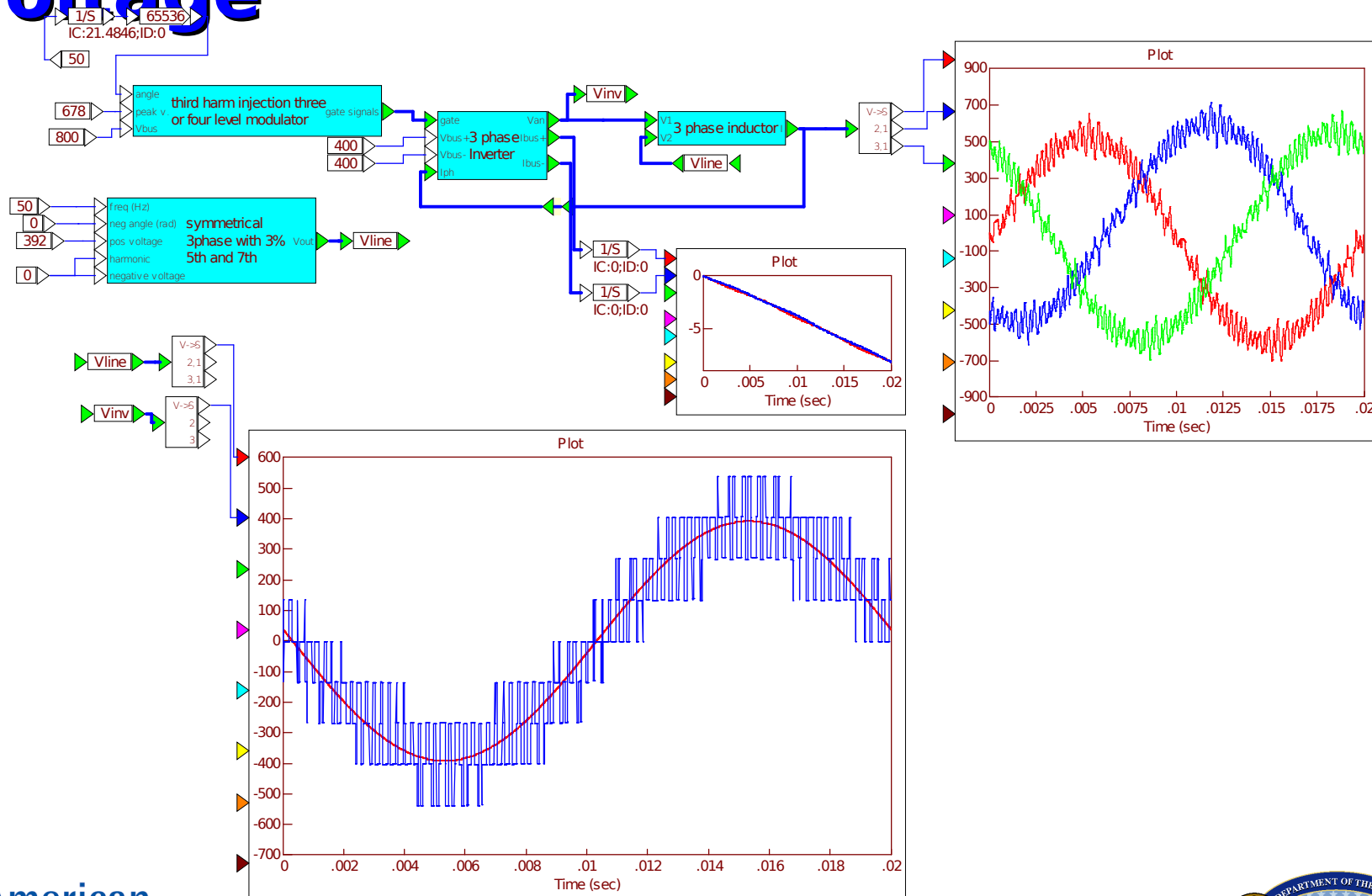
MV Converter Control Features

Power Electronic Systems

- Use basic converter control algorithms from Low Voltage AC-DC and DC-DC Converters
- Multi-level Converters
- Interleaving on DC-DC Converters

MV Simulation: AC-DC Converter

Power Electronic Systems



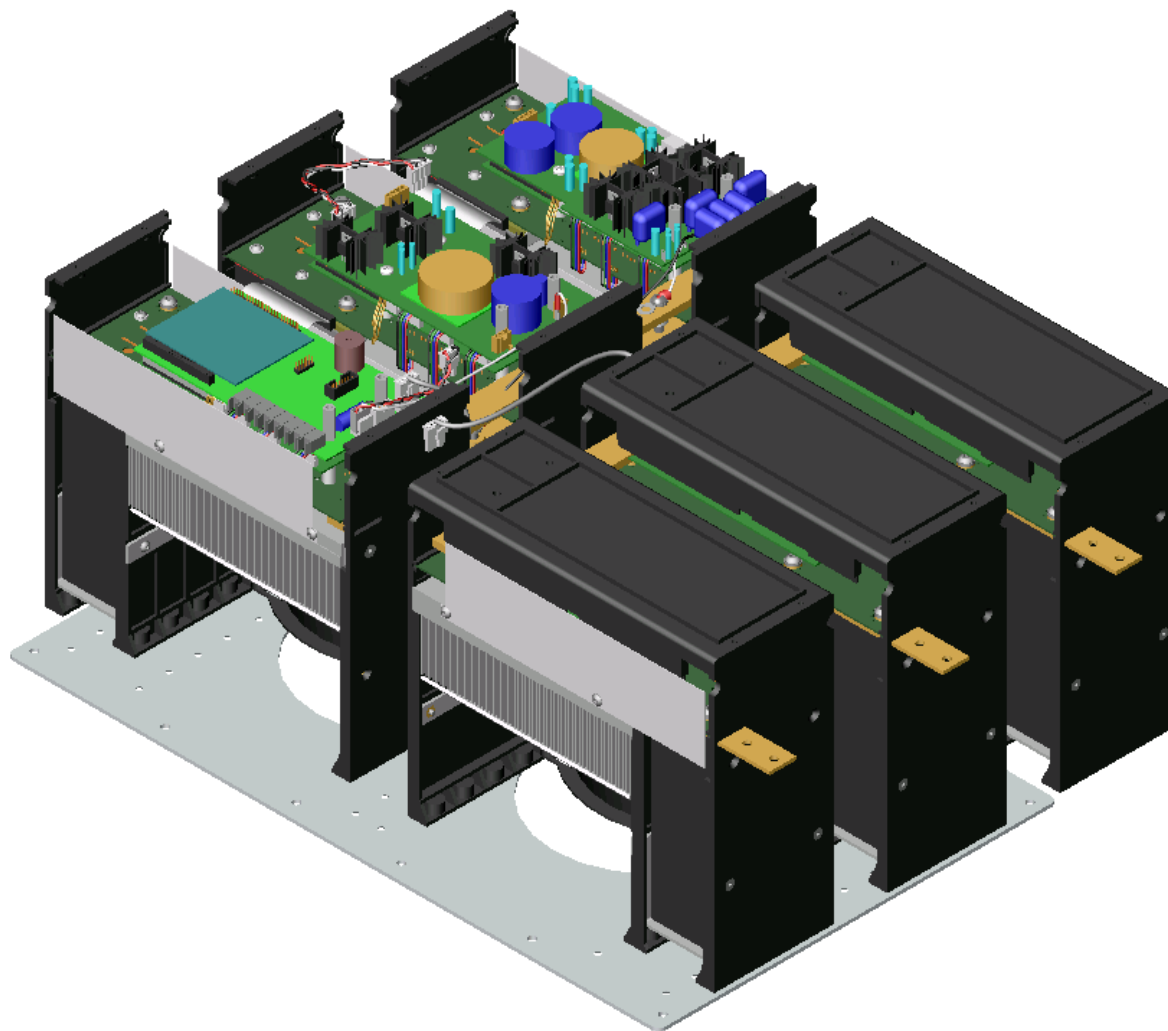
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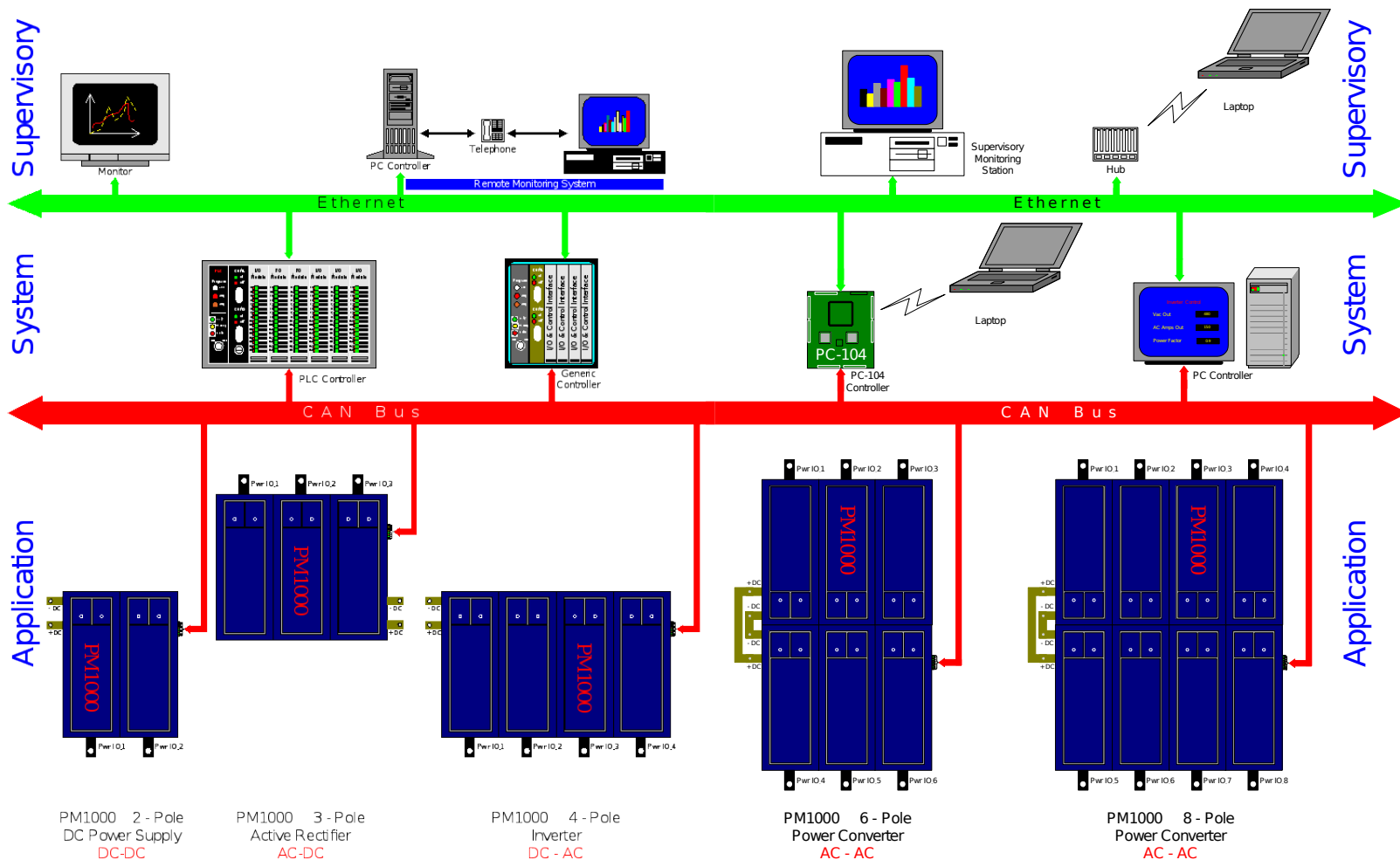
PowerModule Flexibility

Power Electronic Systems



PowerModule Flexibility

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Questions

November 6, 2002